LEO Transportation via Laser Propulsion: Economics and Scenarios

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***Abstract* — Instead of powering a rocket with explosive chemical reactions, an innovative concept, called laser propulsion, involves propelling a rocket by beaming energy to it from outside laser sources. Such a technology would make possible much cheaper access to space. The purpose of this paper is to study the price-per-pound and to identify some scenarios in the cost of LEO transportation using laser propulsion.**

***Keywords* — Laser propulsion, Lightcraft, Economics.**

I. INTRODUCTION

Todays high cost of space transportation is generally viewed as one of the biggest obstacles, if not the biggest, to the growth of space commercialization and exploration. LEO (Low Earth Orbit) payload cost per kg for some chemical rockets most commonly in use are shown in Table I [1].

TABLE I. LEO PAYLOAD COST PER KG FOR SOME CHEMICAL ROCKETS.

ROCKET	LEO CAPABILITY	USD-PER-KG
PEGASUS XL	443 KG	30.474,00
SOYUZ	7 TONS	5.357,00
ARIANE 5	18 TONS	9.167,00
LONG MARCH 3B	13,6 TONS	4.412,00
SPACE SHUTTLE	28,8 TONS	10.416,00

Lightcraft is a revolutionary vehicle whose flight principles, structure, and propulsion systems are radical departures from conventional chemical rockets and whose unique performance will bring easy, safe, and mainly affordable access to space [2].

Conventional chemical rockets must carry combustible material and oxidizers to provide the energy, and therefore must be very large and heavy. On the other hand, ligthcraft carries much less or no propellants, since it gets its working fluid from the atmosphere, and receives the power needed for its propulsion from an outside source such as beamed laser or microwave power (see Fig. 1).

Thus, a major saving in the launch cost or price is possible with ligthcraft technology because of the good-sized and lightweight hardware.

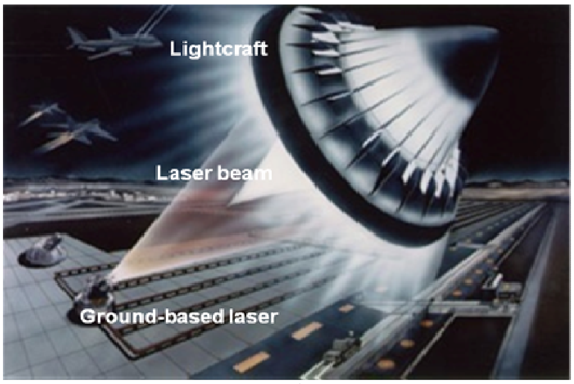

Fig. 1. Artistic view of laser propulsion [3].

To be realistic about lightcraft technology, extensive studies on economics and of the design of lightcraft vehicle along with complex experiments on laser propulsion physics have been pursued by various scientists and engineers around the World. Laser propulsion physics are now much more understood, as laser-induced air breakdown experiments are underway at the Henry T. Nagamatsu Laboratory of Aerothermodynamics and Hypersonic at the Institute for Advanced Studies (IEAv) of the Brazilian Air Force in São José dos Campos, Brazil – in cooperation with U.S. Air Force and the Rensselaer Polytechnic Institute [4]-[6].

Recently, UFABC in Santo André, Brazil has begun the studies on the lightcraft design in partnership with IEAv for future experimentation on laser propulsion physics [7].

Now, we discuss the economics and possible scenarios of LEO transportation via laser propulsion.

II. LIGHTCRAFT ENGINE AND OPERATION

The lightcraft vehicle is an innovative combined-cycle engine (air-breathing and rocket) whose main structures are a forebody, a shroud (inlet) and an afterbody as shown in the photo of Fig. 2. The forebody acts as an airbreathing engine inlet which slows down and compresses the air prior to admission into the ignition chamber of the lightcraft. The afterbody has a dual function: It is the primary receptive optic (parabolic mirror) for the laser beam which provides power to the engine, and it is also a plug nozzle for expansion of the exhaust gas. The primary thrust structure is the annular shroud. The shroud serves as both air inlet (along with the forebody) and impulsive thrust surface.

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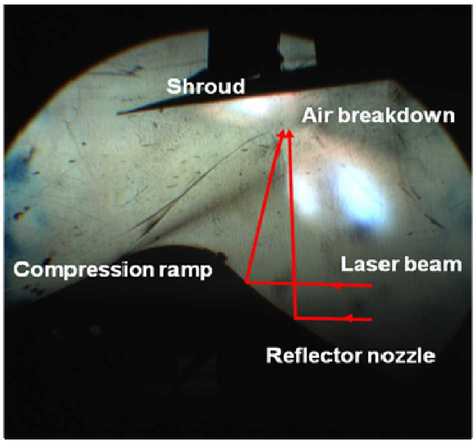

Fig. 2. Cut-view of lighcraft ignition chamber powered with laser beams (Adapted from [7]).

Basically, the operation of the lightcraft vehicle can be described as follows. A pulsed laser light is beamed to the parabolic optic at the rear of the engine and, then, it is reflected and concentrated into the ignition chamber, causing explosion of the air with production of a high temperature and high pressure air plasma. Such plasma soon expands accompanied by a shockwave that interacts directly with the shroud and the plug nozzle, creating momentary elevated pressures which result in impulse. In this way, laser energy is converted into a detonation wave which transfers momentum to the lightcraft vehicle.

III. UFABC LIGHTCRAFT DESIGN AND SIMULATIONS

Recently, UFABC designed a lightcraft vehicle in cooperation with IEAv, as shown in Fig. 3. Also, we performed CFX (Computational Fluid Dynamics) simulations of the hypersonic atmospheric flight of the lighcraft vehicle in cooperation with UNIFEI, as shown in Fig. 4. Our simulations for a laser-unpowered flight at hypervelocities showed the following characteristics: 1. a bow shock ahead of the lightcraft; 2. a very thin shock layer; 3. airflow approximately conical anyplace; and 4. supersonic airflow into the ignition chamber.

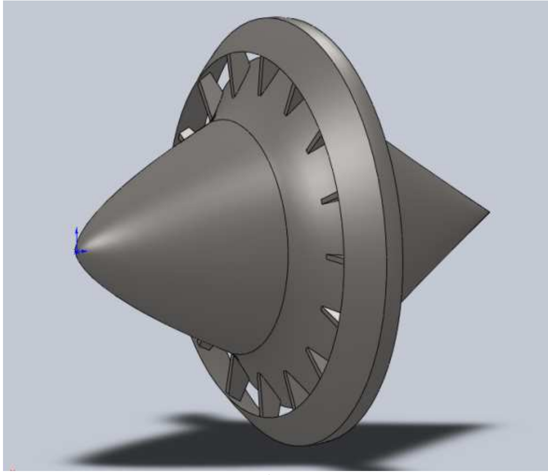

Fig. 3. 3D CAD lightcraft designed by UFABC [7].

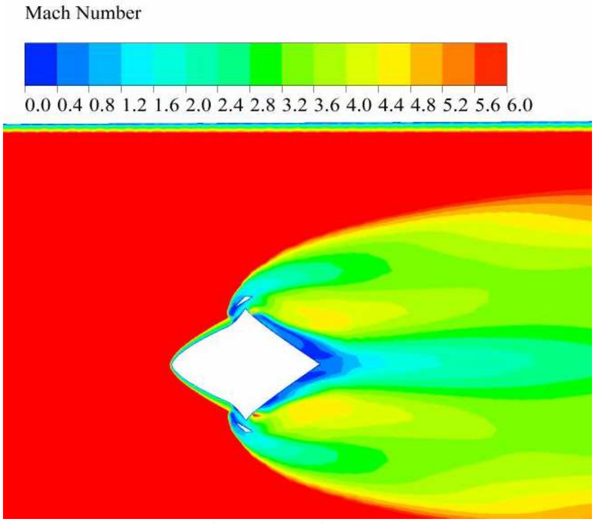

Fig. 4. Flight simulation of the lightcraft at Mach 6 showing a bow shock ahead and a thin shock layer around [7].

IV. ECONOMICS AND SCENARIOS

Now, we exam the economic prospects for launches to LEO with laser propulsion. Scenarios are chosen based upon well-known laser propulsion physics, laser technologies, and launch schemes. Neglecting air drag and gravity, the minimum laser power needed to provide a final mass m_f with a delta-V is [8]:

$$P_{laser} = \frac{1}{2} m_f a_0 V_{jet} \exp\left[\Delta V / V_{jet}\right], \qquad (1)$$

where a_0 is the initial acceleration at the launch, and V_{jet} is the exhaust velocity of the propellant given also by the specific impulse times the Earth's acceleration at sea level, that is, Ig_0. The final mass is the lightcraft mass (airframe, instrumentation etc) plus the payload mass. We choose a final mass of 100 kg, where the payload weighs around 75 kg. Such a payload mass would be equivalent to around 19 micro-satellites of today [9].

Fig. 5 shows the relation between the laser power and exhaust velocity, taking ΔV as a parameter and fixing the mass and acceleration (typical during lift-off, but can be as high as the lightcraft and payload allow). It is clear that the minimum power needed to the launch occurs when $\Delta V / V_{jet} = 1$. From this fact, we will use for now on. Also, note that more power is required as delta-V increases.

A delta-V of 8200m/s is typically needed for LEO altitudes. Thus, from (1), launches to LEO will require at least 22,3 MW of laser power. Now, assuming that the coupling momentum of today, which measures the conversion of laser beam energy into mechanical work which moves the lightcraft, is around 5 % and considering a typical efficiency of conversion between electrical power and laser power of approximately 20%, it is easy to show that at least an electrical power of 2,23 GW will be required to reach LEO.

Numerical simulations of LEO launches via lightcrafts show that the time of flight will last for around 200 seconds [10]. Hence, the lightcraft should consume approximately 123 GWh of electrical energy before reaching LEO altitudes.

LEO launches from Brazil, where the price of the kWh is R$ 0,34472 [11], will cost in total less than R$ 43.000,00 (USD 21.000) per launch. In terms of cost-per-kg of payload into LEO, it would be R$ 569,33 (USD 277), which is much cheaper than the prices shown in Table I for chemical rockets.

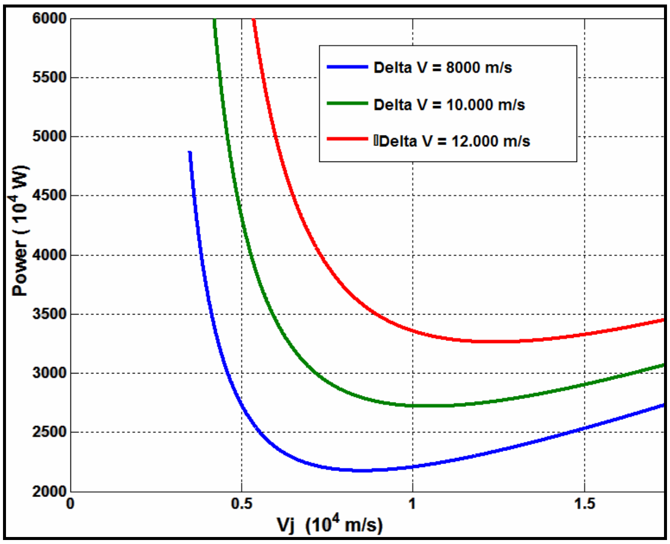

Fig. 5. Laser power needed against exaust velocity, taking delta-V as a parameter.

Fig. 6 shows the electrical power consumption, now including the losses, against exhaust velocity for various LEO altitudes. As we can see, the blue line is the previous scenario discussed, and the worst as well because the losses are high. Thus, consumption of electrical power to supply the laser device is lowered as the exhaust speed of the hot gas increases whatever delta-V. Finally, taking into account the price per kWh of electrical energy in Brazil, losses and the payload capability, the price-per-kg of payload transported to LEO via laser propulsion can be easily obtained, as shown in Fig. 7.

The prices shown in Fig. 7 may increase by around 1,3 times (at worst case) because of the following reasons: 1. Neglect of 20 % of losses due drag during atmospheric flight and gravity in (1); 2. No loss due to absorption of the laser beam as it passes the entire atmosphere (at worst case, around 5 % of loss with infrared laser beams); and 3. No laser range limitations. Also, we did not consider changes in price due to costs associated to the construction the lightcraft in itself and the launch site infrastructure such as laser sources, tracking and guidance system, and power plant. Note that, prices tend to increase as the exhaust velocity does not meet the delta-V of the mission, which is not good.

Operational costs of the launches via lightcraft are dominated by maintenance costs of the lightcraft and launch site. Thus, even countries with a very low annual space budget of USD 20 million (case of Brazil) would have some 1000 launches of 75-kg payloads per year with a competitive price of 21.000 USD per launch via laser propulsion.

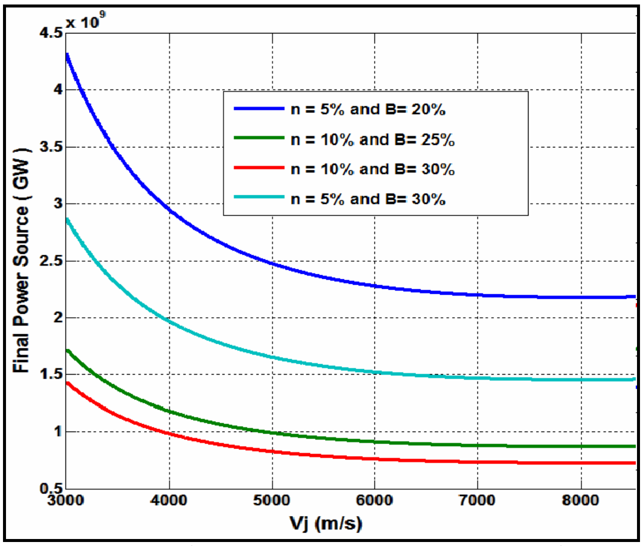

Fig. 6. Consumption of electrical energy against exhaust velocity for various energy efficiencies.

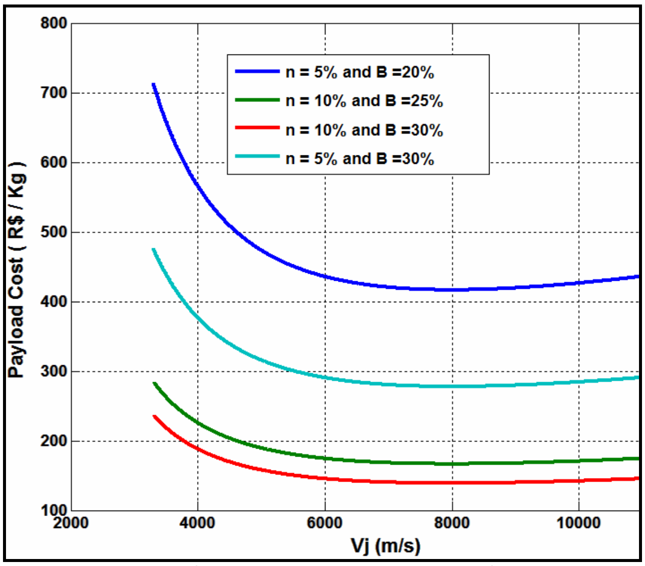

Fig. 7. Price-per- kg of payload against exhaust velocity for various energy efficiencies.

When the laser beam passes the atmosphere many optical distortions may occur due to turbulence and the beam quality is maintained only if a good adaptive optical system [8] is available at the launch site. In combination with the adaptive optical system, a solution would be the construction of the launch site atop a mountain.

The range z of the laser is defined as the distance, where the diameter of the beam starts to become larger than the diameter of lightcraft receiver, i.e., the shroud diameter. The range depends on the wavelength of the laser λ, the diameter of the telescope (transmitting optic mirror) D, the shroud diameter d, and the ability of the optical system to compensate the atmosphere distortions, known as Strehl ratio Str.

For d << D, the laser range z is given by [8]:

$$z = \frac{dD\sqrt{Str}}{2.44\lambda}, \qquad (2)$$

Assuming Str between 0,3 and 0,5 [8], and admitting a receiver shroud diameter of 20 cm (diameter of the UFABC lightcraft prototype), and taking D as a parameter, we can plot the range of the laser as function of the wavelength, as shown in Fig. 8.

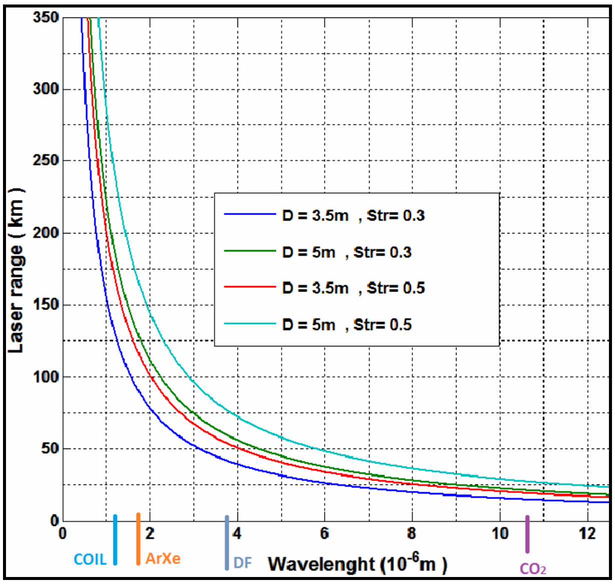

Fig.8. Laser range against laser wavelength taking the Strehl ratio and the diameter of the transmitting optic mirror as parameters.

It is clear the need of higher diameters of transmitting telescopes at the launch site and shorter wavelengths to have laser ranges up to LEO altitudes of 100 km. The Chemical Oxygen-Iodine Laser (COIL) is superior over other infrared laser devices shown not only because of the short wavelength of 1,3 µm but also due to the current availability of megawatt COIL laser devices [12].

V. CONCLUSION

Laser propulsion is a new economical and green way to launch miniaturized satellites into LEO, in comparison with conventional chemical propulsion. We found that lightcraft is a promising technology for space commercialization within some decades due to its very competitive low price-per-kg of payload: Around two orders of magnitude lower than current prices. Further studies on economics of laser propulsion have to be made in order to be more precise about its total cost including the suitable laser device, an adaptive optical system and launch site issues.

ACKNOWLEDGEMENTS

The first author thanks the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) for providing his scholarship.

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